III.C.2 Development of a New Class of Low-Cost, High-Frequency Link Direct DC-to-AC Converters for SOFCs

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Objectives

- To develop a new and innovative power converter technology suitable for solid oxide fuel cell (SOFC) power systems in accordance with the Solid State Energy Conversion Alliance (SECA) objectives.
- To realize a cost-effective fuel cell converter which operates under a wide input voltage range and output load swings with high efficiency and improved reliability.

Approach

- Employ state-of-the-art power electronic devices configured in two unique topologies to achieve direct conversion of DC power (24-48 V) available from a SOFC to AC power (120/240 V, 60 Hz) suitable for utility interface and powering stand-alone loads.
- Investigate the feasibility of two direct DC-to-AC converter topologies and their suitability to meet SECA objectives.

Accomplishments

- A 3-kW converter has been successfully constructed and tested. An overall efficiency (from fuel cell input DC to 120 V AC output) of 90% was measured. There is still room for improvement by reducing the transformer leakage and by improving the four-step switching strategy of the bidirectional switches.
- Due to absence of dc-link capacitors, a low-profile converter construction can be adopted, resulting in a higher-density package.
- An optimized 2nd order input filter at the input terminals guarantees the fuel cell input current is nearly devoid of current ripple.

Future Directions

- The converter construction and design will be further optimized for higher efficiency.
- The usage of silicon carbide (SiC) semiconductors will facilitate the converter operation at higher temperature. This needs to be explored further.

Introduction

This project proposes to design and develop a new class of power converters (direct DC to AC) to drastically improve performance and optimize the cost, size, weight and volume of the DC-to-AC converter in SOFC systems. The proposed topologies employ a high-frequency link, direct DC-to-AC conversion approach. The direct DC-to-AC conversion approach is more efficient and operates without an intermediate dc-link stage. The absence of the dc-link results in the elimination of bulky, aluminum electrolytic capacitors, which in turn leads to a reduction in the cost, volume, size and weight of the power electronic converter.

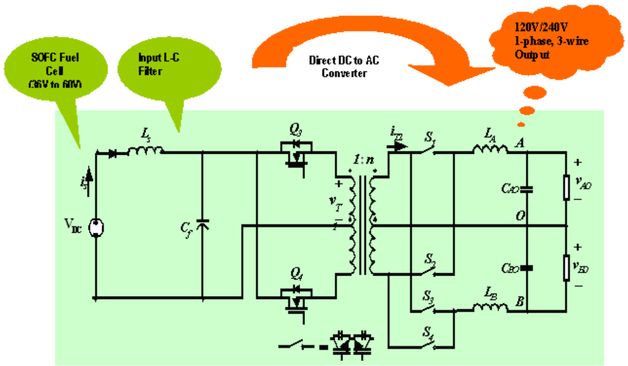

Figure 1. Proposed Voltage Source Type Direct DC-to-AC Converter for SOFC without a Battery

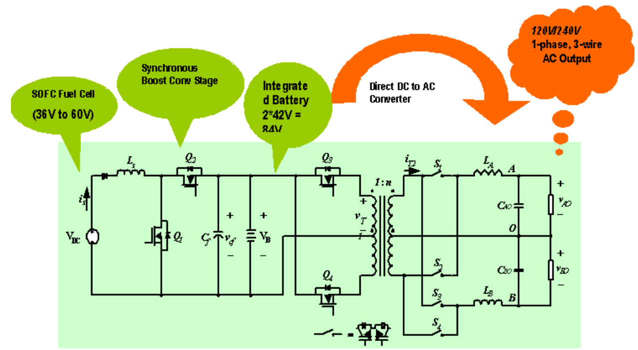

Figure 2. Proposed Voltage Source Type Direct DC-to-AC Converter for SOFC PCU with an Integrated Battery

The feasibility of two direct DC-to-AC converter topologies and their suitability to meet SECA objectives have been investigated. Laboratory prototype converters (3-5 kW) have been designed and tested in Phase 1.

Approach

Figure 1 shows the complete topology of the first direct DC-to-AC converter. In this approach, the fuel cell DC input voltage is processed via a high-frequency link MOSFET (metal-oxide-semiconductor field-effect transistor) converter via transformer isolation.

The high-frequency transformer provides isolation as well as facilitates the step-up in voltage. The secondary side converter is composed of bi-directional switches, which directly convert to low-frequency AC output. Two MOSFET switches (Q3 and Q4) are connected in push-pull fashion for converting the SOFC voltage (36 V) to high frequency, and the secondary transformer is interfaced with switches S1 to S4 to transform direct DC to 1-phase 120-V/240-V, 60-Hz, 3-wire AC output.

From the technical specifications obtained from Delphi for the SOFC power conditioning unit (PCU), it is clear that a battery backup option needs to be explored for the PCU to satisfy stand-alone and uninterrupted power supply (UPS) modes of operation. In order to comply with these specifications, the converter topology shown in Figure 1 has been modified as shown in Figure 2.

Figure 2 shows the direct DC-to-AC converter topology with integrated battery backup concept suitable for operating modes Mode 1 and Mode 4. In this approach, the SOFC output (36 V to 60 V) is first processed via a synchronous boost converter and is converted to 84 V. Two 42-V batteries (connected in series to obtain 84 V) are connected at the output of the boost stage. The direct DC-to-AC converter stage then converts the 84-V DC to 120-V/240-V 1-phase 3-wire output. The push-pull stage of the direct DC-to-AC converter in this design (Figure 2) sees a fixed 84-V DC at its input, and its design is optimized for full-load operation of 5 kW. Comparing Figure 1 and Figure 2, one notes that the direct DC-to-AC converter along with the high-frequency transformer in Figure 2 will be smaller in size and more efficient than the converter design in Figure 1. This increase in conversion efficiency is expected to be offset by the addition of the synchronous boost stage in Figure 2. Therefore, the overall efficiency of Figure 1 and Figure 2 designs should be comparable. Integrating the battery within the power conversion stage has many advantages and can meet the Delphi-described PCU operating modes 1 and 4.

Results

Texas A&M University (TAMU) design for the proposed converter has centered around the specifications obtained from Delphi and General Electric. Table 1 and Table 2 show the converter component ratings to meet the specifications. Figures 3, 4, and 5 show the waveforms obtained from simulations.

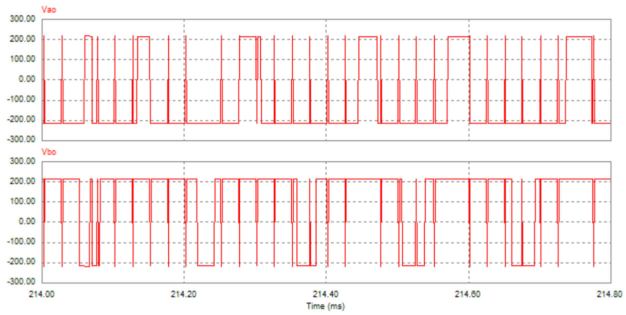

Figure 3. Unfiltered Output Voltage of the Direct DC-to-AC Converter Shown in Figure 1 and Figure 2

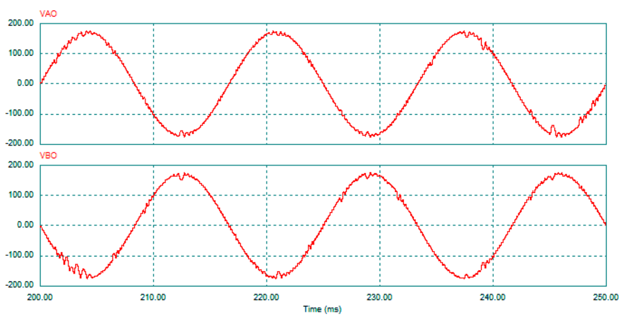

Figure 4a. Single-phase 120-V/240-V, 60-Hz, 3-wire Output Voltage of the Direct DC-to-AC Converter of Figure 1 and Figure 2

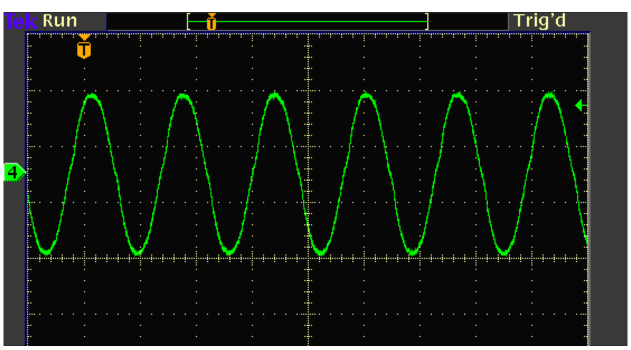

Figure 4b. Experimental Results (output ac voltage for phase A)

Output power: 5 kW (resistive)

Output voltage: 120-V/240-V, 1-phase, 60-Hz, 3-wire output

Output current: 20.7 A (rms.), 29.3 A (peak)

Switching frequency: 20 kHz

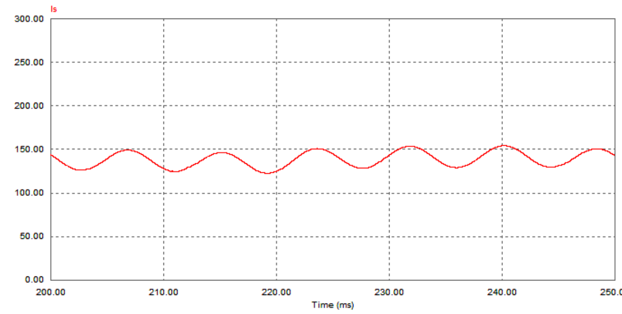

Figure 5. Fuel Cell Input Current Waveform

Table 1. Converter Component Ratings to Meet the Specifications

Input voltage Vdc [V]	Turn ratio N2/N1	L_1 [uH]	L_2 [nH]	C_1 [F]	C_2 [F]	L_A [mH]	C_{AO} [uF]
36	16/3	1	5	30	0.5	1	50

Table 2. Converter Component Ratings to Meet the Specifications (Con't)

Vi [V]	$V_{Q3.rms}$ [V_{rms}]	$I_{Q3.pk}$ [A]	$V_{S1.rms}$ [V_{rms}]	$I_{S1.pk}$ [A]	$I_{A,rms}$ [A_{rms}]	$I_{A,pk}$ [A]	$I_{T2,rms}$ [A_{rms}]	$I_{T2,pk}$ [A]
36	50.7 0.42p.u	365.5 12.5 p.u	270.8 2.3 p.u	32.1 1 .1p.u	21.1 1 p.u	32.4 1.1 p.u	19.7 0.95p.u	33.6 1.1p.u

Conclusions

From the results obtained in Phase 1, it can be concluded that the topologies shown in Figure 1 and Figure 2 have several advantages compared to the prior state-of-the-art. A 3-kW converter has been successfully constructed and tested. An overall efficiency of 90% was measured. There is still room for improvement by reducing the transformer leakage and by improving the four-step switching strategy of the bidirectional switches. These approaches will be pursued in Phase 2 of the project. Due to absence of dc-link capacitors, a low-profile converter construction can be adopted, resulting in a higher-density package. Higher reliability is achievable because the control of the primary side push-pull converter is simple and operates at 50% fixed duty cycle. Zero voltage switching of the switching converter on the primary side can be achieved using magnetizing current inherent in the high-frequency transformer. This aspect is under further investigation. An optimized 2nd order input filter at the input terminals guarantees the fuel cell input current to contain minimum input current ripple. The output of the converter can be altered from 1-phase to 3-phase by a simple change in software.

References

1. S. Kim, S. K. Sul and T. A. Lipo, "AC/AC Power Conversion Based on Matrix Converter Topology with Unidirectional Switches", IEEE Trans. IA, Vol. 36, No. 1, pp. 139-145, 2000

2. V. Kaura and V. Blasko, "Operation of a Voltage Source Converter at Increased Utility Voltage", IEEE Trans. PE, Vol. 12, No. 1, pp. 132-137, January, 1997

3. N. Mohan, T. M. Undeland and W. P. Robbins, "Power Electronics: Converters, Applications, and Design" 3rd Edition

FY 2004 Publications/Presentations

1. Yu Jin Song, P. Enjeti, "A High Frequency Link Direct DC-AC Converter for Residential Fuel Cell Power Systems", IEEE Power Electronics Specialist Conference, PESC 2004, June 2004

Special Recognitions & Awards/Patents Issued

1. Patenting process initiated via TAMU technology licensing office.